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PRECIPITATION CRITERIA GUIDELINES FOR USE IN AEROSPACE VEHICLE DEVELOPMENT

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This document provides guidelines on probable precipitation extremes and characteristics applicable for NASA space vehicles and associated equipment development. Information is provided on probability of rainfall rates, drop size, drop rate of fall, associated wind speeds with rainfall, snow loads, hail, laboratory test simulation, and rain erosion.

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PRECIPITATION CRITERIA GUIDELINES FOR USE IN AEROSPACE VEHICLE DEVELOPMENT

SUMMARY

In previous documents, such as the Terrestrial Environment (Climatic) Criteria Guidelines for use in Space Vehicle Development [1], rates of precipitation at the ground surface were mainly considered on the basis of water tightness of compartments and frost accumulation on LOX tanks while the vehicle was on the launch pad. This frost was generally released from the vehicle at launch time by vibration.

With future development of recoverable vehicles which fly horizontally on return and during ferrying operations, additional considerations of precipitation in abrasion and accumulation of ice on fuel tanks are required.

1.0 Introduction

Of all the atmospheric parameters quantitatively measured routinely, precipitation is the only one occurring in discrete events. In some desert areas of the world, precipitation does not occur for several years. Even in areas of moderate to heavy rainfall, there are many periods of time without rain. Because precipitation does occur in discrete events, statistical presentations may be misleading unless accompanied with appropriate explanations. Precipitation occurs in a variety of forms, with most of the differences of form as a result of the temperature. Definitions used in this report are given in following paragraphs.

Precipitation is usually defined as all forms of hydrometeors, liquid or solid, which are free in the atmosphere and which reach the ground. In this report the definition is extended to those hydrometeors which do not reach the ground, but impinge on a flying surface, such as space vehicles. Accumulation is reported in depth over a horizontal surface; i.e., millimeters or inches for the liquid phase and in depth or equivalent depth of water equivalent for the frozen phase.

Snow is defined as all forms of frozen precipitation except large hail. It encompasses snow pellets, snow grains, ice crystals, ice pellets, and small hail.

Hail is precipitation in the form of balls or irregular lumps of ice and is always produced by convective clouds. Through established convention the diameter of the ice must be 5 mm or more, and the specific gravity between 0.60 and 0.92 to be classified as hail.

Freezing rain is rain that falls in liquid form but freezes upon impact to form a coating of glaze upon the ground or exposed objects.

Small hail is precipitation in the form of semitransparent, round, or conical grains or frozen water under 5 mm in diameter. Each grain consists of a nucleus of soft hail (ball of snow) surrounded by a very thin ice layer. They are not crisp and do not usually rebound when striking a hard surface.

These precipitation forms are sufficiently different that each needs to be considered separately in design problems.

2.0 Rainfall

There are four major rainfall-producing atmospheric conditions. (1) the monsoon which produces the heaviest precipitation over long periods (most world records of rainfall rates for periods greater than 12 hr are a result of monsoons), (2) thunderstorms which generate high rates of precipitation for short periods, (3) cold and warm frontal systems, frequently accompanied by bands of steady light rain which fall at any one station for periods up to a maximum of approximately three days (thunderstorms may occur with frontal systems to give heavier rain), and (4) hurricanes which produce heavy rain associated with winds. These four rainfall types are defined in the following paragraphs.

Monsoon: The monsoon is a seasonal wind which blows for long periods of time, usually several months from one direction. When these winds blow from the water to land with increasing elevation from the water, the orographic lifting of the moisture-laden air releases precipitation in heavy amounts. In Cherrapunji, India 9144 mm (360 in.) of rain has fallen in a one-month period from monsoon rains. The amount of rain from monsoons at low elevations is considerably less than at higher elevations.

Thunderstorm: In general a thunderstorm (local storm) is produced either by lifting of unstable moist air, heating of the land mass, lifting by frontal systems or a combination of these conditions. Cumulonimbus clouds, which are produced by these storms, are always accompanied by lightning and thunder. The thunderstorm is a consequence of atmospheric instability and is defined loosely as an overturning of air layers in order to achieve a stable condition. Strong wind gusts, heavy rain, and sometimes hail occurs with the thunderstorm with the most frequent and severe occurrences in the late afternoons.

Cold and Warm Front Precipitation: When two masses of air-one more dense than the other-meet, the lighter air mass (warm) will slide up over the more dense air mass (cold). If sufficient moisture is in the air mass being lifted, then the moisture will be condensed out and fall as precipitation, either rain or snow, depending on the temperatures of air masses.

Hurricanes: A hurricane is a severe "tropical cyclone" which forms over the various oceans and seas almost always in tropical latitudes. At maturity the tropical cyclone is one of the most intense and feared storms in the world; winds exceeding 90 m sec^{-1} (175 knots) have been measured, and its rainfall can be torrential. The wind speed must exceed 33 m sec^{-1} (64 knots) to be a hurricane.

2.1 Record Rainfall

In design analysis, the maximum amounts of rainfall for various periods need to be considered. These extreme values vary considerably in different areas of the world, but in areas of similar climatic conditions the extreme values are similar.

2.1.1 World Record Rainfall

To best study the maximum amounts of rainfall that have occurred worldwide for different periods, log-log graph paper is used. Figure 1 shows these worldwide values and the envelope of these values as a straight line with the equation

$$R = 36.3\sqrt{D} \tag{1}$$

where

R = Depth of Rainfall in mm for period D.
D = Duration of Rainfall in hours.

2.1.2 Design Rainfall Rates

For design and testing, the rate of rainfall per unit time is more useful than the total depth of rainfall. The normal rates used are shown in millimeters per hour or inches per hour. Figure 2 shows the envelope of world record values plotted as the rate per hour (inches and millimeters) versus duration.

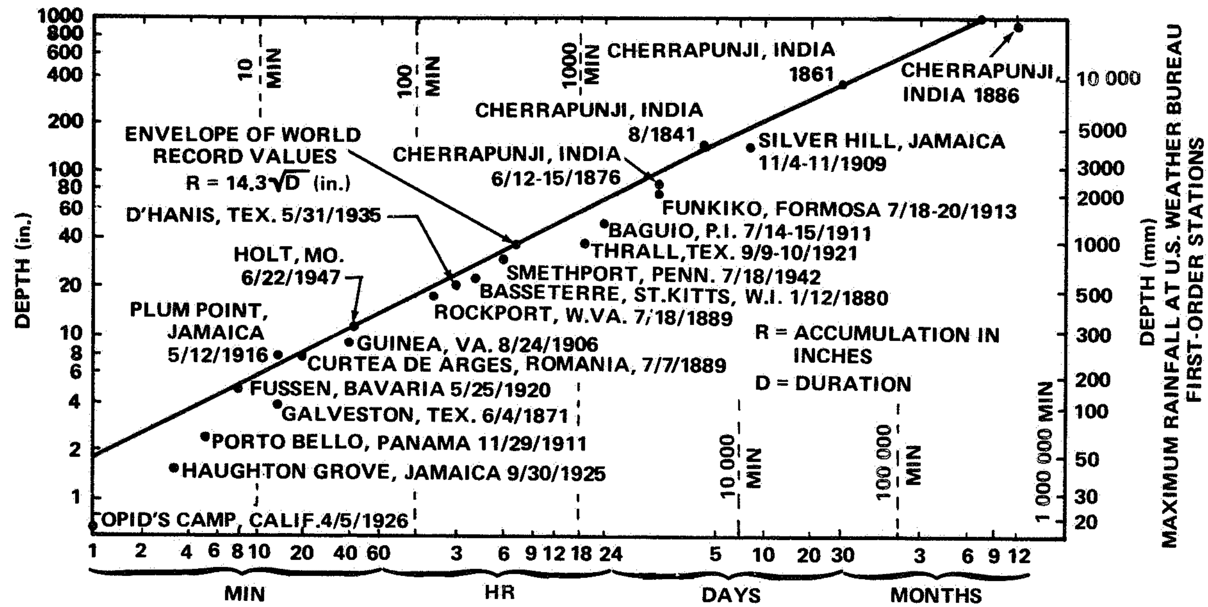

Figure 1. World record rainfalls and an envelope of world record values. (After R. D. Fletchter and D. Sartos, Air Weather Service Tech. Rept. No. 105-81, 1951.)

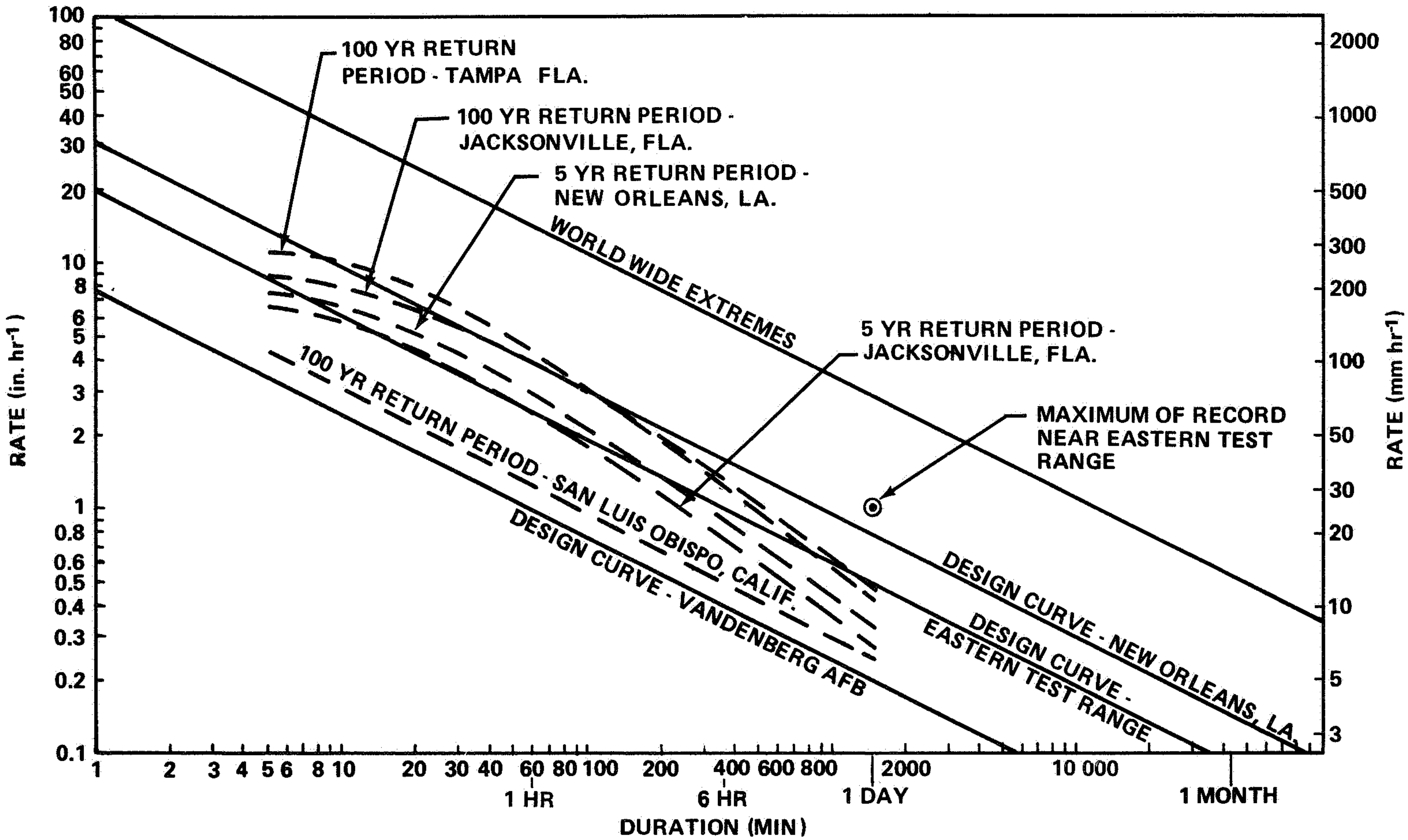

Figure 2. Design rainfall rates.

The design rainfall rate curves are also shown in Figure 2 with 5-yr and 100-yr return period data for a few selected stations. The 5-yr and 100-yr return period data are from Rainfall-Intensity-Duration-Frequency Curves published by the U. S. Department of Commerce, Weather Bureau [2]. This data was analyzed by the Extreme Value Method of Gumble [3].

The term "return period" is frequently used in statistics relating to precipitation. Return periods can be expressed as probabilities as shown in Table 1.

TABLE 1. RELATIONSHIP OF RETURN PERIODS TO PROBABILITIES

Return Period	Percentile	Return Period	Percentile
(yr)	(%)	(yr)	(%)
2	50	50	98
5	80	100	99
10	90	1000	99.9

Values of design rainfall for various locations and world-wide extremes of rainfall are given in Tables 2, 3, 4, and 5 with values of the corresponding drop size, wind speeds, and temperature. The world-wide extremes (Table 5) would not normally be used for design of space vehicles but may be needed for facility design, tracking stations, etc. The values of rainfall rates are represented with the following equation (curve fit to graphical values of Fig. 2):

$$r = \frac{C\sqrt{D}}{D} = \frac{C}{\sqrt{D}} \qquad (2)$$

where

r = rate per hour
D = Time in minutes
C = Constant for location as given in Table 6.

2.2 Raindrop Size

A knowledge of raindrop sizes is required to: (1) simulate rainfall tests in the laboratory, (2) know the rate of fall of the raindrops and impact energy, and (3) use in erosion tests of materials.

TABLE 2. DESIGN RAINFALL, KENNEDY SPACE CENTER, FLA.; HUNTSVILLE, ALA.; AND WALLOPS TEST RANGE, VA.; BASED ON YEARLY LARGEST RATE FOR STATED DURATIONS

Time Period	Rainfall Rate		Rainfall Total Accumulation		Raindrop Size		Average Rate of Fall	Wind Speed		Duration of Peak Wind	Air Temperature (°F)			
					Average	Largest		Average	Peak		Summer		Winter	
	mm hr^{-1}	in. hr^{-1}	mm	in.	mm	mm	m sec^{-1}	m sec^{-1}	m sec^{-1}	min	Start	During	Start	During
1 min	492	19.4	8	0.3	2.0	6.0	6.5	5.0	16.0	0.5	90	75	55	50
5 min	220	8.7	18	0.7	2.0	5.8	6.5	5.0	16.0	0.5	90	75	55	50
15 min	127	5.0	32	1.25	2.0	5.7	6.5	5.0	16.0	0.5	90	75	55	50
1 hr	64	2.5	64	2.5	2.0	5.0	6.5	5.0	16.0	0.5	90	75	55	50
6 hr	26	1.0	156	6.1	1.8	5.0	6.5	5.0	16.0	0.5	90	75	55	50
12 hr	18	0.7	220	8.7	1.6	4.5	6.5	5.0	16.0	0.5	90	75	55	50
24 hr	13	0.5	311	12.2	1.5	4.5	6.5	5.0	16.0	0.5	90	75	55	50

TABLE 3. DESIGN RAINFALL, NEW ORLEANS, LA.; BASED ON YEARLY LARGEST RATE FOR STATED DURATIONS

Time Period	Rainfall Rate		Rainfall Total Accumulation		Raindrop Size		Average Rate of Fall	Wind Speed		Duration of Peak Wind	Air Temperature (°F)			
					Average	Largest		Average	Peak		Summer		Winter	
											Start	During	Start	During
	mm hr^{-1}	in. hr^{-1}	mm	in.	mm	mm	m sec^{-1}	m sec^{-1}	m sec^{-1}	min				
1 min	787	31.0	13	0.5	2.1	6.0	6.5	5.0	16.0	0.5	90	75	55	50
5 min	352	13.9	29	1.2	2.0	6.0	6.5	5.0	16.0	0.5	90	75	55	50
15 min	203	8.0	51	2.0	2.0	5.7	6.5	5.0	16.0	0.5	90	75	55	50
1 hr	102	4.0	102	4.0	2.0	5.5	6.5	5.0	16.0	0.5	90	75	55	50
6 hr	41	1.6	249	9.8	1.9	5.0	6.5	5.0	16.0	0.5	90	75	55	50
12 hr	29	1.2	352	13.9	1.8	5.0	6.5	5.0	16.0	0.5	90	75	55	50
24 hr	21	0.8	498	19.6	1.6	5.0	6.5	5.0	16.0	0.5	90	75	55	50

TABLE 4. DESIGN RAINFALL, VANDENBERG AFB (SAMTEC), CALIF.; EDWARDS AFB, CALIF.; AND WHITE SANDS MISSILE RANGE, N.M.; BASED ON YEARLY LARGEST RATE FOR STATED DURATIONS

Time Period	Rainfall Rate		Rainfall Total Accumulation		Raindrop Size		Average Rate of Fall	Wind Speed		Duration of Peak Wind	Air Temperature (°F)			
					Average	Largest		Average	Peak		Summer		Winter	
	mm hr^{-1}	in. hr^{-1}	mm	in.	mm	mm	m sec^{-1}	m sec^{-1}	m sec^{-1}	min	Start	During	Start	During
1 min	197	7.7	3	0.1	2.0	5.6	6 5	4.0	16.0	0.5	90	75	55	50
5 min	88	3.5	7	0.3	2.0	5.3	6.5	4.0	16.0	0.5	90	75	55	50
15 min	51	2.0	13	0.5	2.0	5.0	6.5	4.0	16.0	0.5	90	75	55	50
1 hr	25	1.0	25	1.0	1.8	5.0	6.5	4.0	16.0	0.5	90	75	55	50
6 hr	10	0.4	62	2.4	1.5	4.6	6.0	4.0	16.0	0.5	90	75	55	50
12 hr	7	0.3	88	3.5	1.3	4.3	5.8	4.0	16.0	0.5	90	75	55	50
24 hr	5	0.2	124	4.9	1.3	4.0	5.5	4.0	16.0	0.5	90	75	55	50

TABLE 5. DESIGN RAINFALL, WORLDWIDE EXTREMES, BASED ON YEARLY LARGEST RATE FOR STATED DURATIONS

Time Period	Rainfall Rate		Rainfall Total Accumulation		Raindrop Size		Average Rate of Fall	Wind Speed		Duration of Peak Wind	Air Temperature (°F)			
					Average	Largest		Average	Peak		Summer		Winter	
	mm hr^{-1}	in. hr^{-1}	mm	in.	mm	mm	m sec^{-1}	m sec^{-1}	m sec^{-1}	min	Start	During	Start	During
1 min	2813	110.8	47	1.8	2.5	6.0	6.5	NA	NA	NA	90	75	55	50
5 min	1258	49.5	105	4.1	2.2	6.0	6.5	NA	NA	NA	90	75	55	50
15 min	726	28.6	182	7.1	2.1	6.0	6.5	NA	NA	NA	90	75	55	50
1 hr	363	14.3	363	14.3	2.0	6.0	6.5	NA	NA	NA	90	75	55	50
6 hr	148	5.8	890	35.3	2.0	5.8	6.5	NA	NA	NA	90	75	55	50
12 hr	105	4.1	1258	49.5	2.0	5.5	6.5	NA	NA	NA	90	75	55	50
24 hr	74	2.9	1779	70.1	2.0	5.2	6.5	NA	NA	NA	90	75	55	50

TABLE 6. CONSTANTS TO USE WITH EQUATION (2) FOR RAINFALL RATES

	Eastern Test Range Huntsville, Wallops Test Range	New Orleans	Vandenberg AFB (SAMTEC) Edwards AFB, White Sands Missile Range	World-wide Extremes
in. hr^{-1} mm hr^{-1}	19.365 491.87	30.984 786.99	7.746 196.75	110.767 2813.48
Values given in Table No.	2	3	4	5

At the surface, the size of the raindrops vary with the rate of rainfall per unit time, the heavier the rainfall, the larger the drops. Any one rainstorm will contain a variety of sizes of raindrops ranging in size from less than 0.5 mm (the lower limit of size measurement) to greater than 4.0 mm. The more intense the storm (higher the rate of fall) the larger some of the drops will be. Reference 4 shows data on probability of occurrence of various raindrop sizes with relation to types of rain-producing storms; (1) thunder storms, (2) rain showers, and (3) continuous rain. Thunderstorms have the greatest occurrence of the larger drops (over 2 mm). Rain showers have the next greatest occurrence, while the continuous rain produces the lowest occurrence of the larger drops. Raindrop sizes below 2-mm diam. occur with near equal probability from all types of storms. In comparing drop sizes with various rainfall rates, the larger drops occurred with the highest probability from the highest rainfall rates. Raindrops over 6 mm in diameter are not expected to occur frequently because the rate of fall breaks these large drops into smaller ones.

2.3 Statistics of Rainfall Occurrences

One set of statistical data on precipitation will not be satisfactory for all needs in design; therefore, several sets of statistical data are presented in this section as follows:

2.3.1 Design Rainfall Rates

The design rainfall rates in Figure 2 and Tables 2, 3, 4, and 5 are based on precipitation occurrences; i.e. if precipitation is occurring what is the probability of exceeding a rate? This data is based on occurrences over a year and would be used in design of items continuously exposed, such as launch facilities.

2.3.2 Probability that Precipitation Will Not Exceed a Specific Amount in Any One Day

Values for each month with the probability that precipitation will not exceed a specified amount in any one day are given for several selected sites of Aerospace vehicle design interest-Cape Kennedy, Fla.; Edwards Air Force Base and Vandenberg Air Force Base, Calif.; New Orleans, La.; and Wallops Test Range, Va. in Tables 7, 8, 9, 10, and 11 respectively. The values in the tables should not be interpreted to mean that the amount of precipitation occurs uniformly over the 24-hr period, since it is more likely that most or all of the amounts occurred in a short period of the day.

2.3.3 Rainfall Rates Versus Duration for 50th, 95th, and 99th Percentile, Given a Day with Rain for the Highest Rain Month, Kennedy Space Center, Fla.

Rainfall rates for various durations for the 50th, 95th, and 99th percentiles, given a day with rain in the highest rain month are given in Table 12 for Kennedy Space Center, Fla. The values for precipitation amounts over the duration given should not be interpreted to mean that the amount of precipitation occurred uniformly over the period, since it is possible to have had the total amount of the rain (at rates as high as those given in Table 2) in a shorter period of time within the duration to obtain the total rate for the period. The 99th percentile total of 49 mm (1.93 in.) (Table 12) could have occurred as 7.6 mm (0.3 in.) in 1 min, 17.8 mm (0.7 in.) in 5 min, and 23.6 mm (0.93 in.) in 11 min [at 15-min rate of 132 mm (5.0 in. hr^{-1})] at rates as high as those in Table 2.

2.4 Distribution of Rainfall Rates with Altitude

Rainfall rates normally decrease with altitude when rain is striking the ground. The rainfall rates at various altitudes in percent of the surface rates are given in Table 13 for all areas [5].

Precipitation above the ground is generally colder than at the ground and frequently occurs as supercooled drops which may cause icing on objects moving through the drops. Such icing can be expected to occur when the air temperature is -2.2° C (28° F). The amount of icing (i.e., rate of formation) is related to the speed and shape of the object. For the geographic areas considered in this report, these conditions usually occur between 30- and 10-km altitude.

TABLE 7. PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY, CAPE KENNEDY, FLA.

Amount		Jan	Feb	March	Apr	May	June
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	68.1	60.8	62.2	70.6	64.2	54.7
Trace	Trace	77.1	71.4	71.3	80.0	76.2	65.7
0.01	0.25	79.0	74.3	72.5	82.7	79.4	68.4
0.05	1.27	84.8	79.4	77.5	86.6	84.7	74.1
0.10	2.54	87.1	82.3	81.6	89.3	89.4	75.8
0.25	6.35	90.0	85.8	87.8	93.5	92.9	82.8
0.50	12.70	93.9	91.6	91.6	95.9	96.4	90.8
1.00	25.40	97.1	96.1	96.3	98.0	99.3	97.1
2.50	63.50	99.4	100.0	99.5	99.5	100.0	99.8
5.00	127.00	100.0	100.0	99.8	99.8	100.0	100.0
Amount		July	Aug	Sept	Oct	Nov	Dec
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	56.8	52.6	40.0	47.4	62.1	64.2
Trace	Trace	65.8	63.9	53.9	61.6	74.2	78.1
0.01	0.25	68.4	66.2	57.5	63.9	77.2	81.0
0.05	1.27	73.2	69.4	62.7	72.0	83.9	86.8
0.10	2.54	75.8	74.9	67.9	76.8	86.9	89.4
0.25	6.35	83.5	80.7	75.8	85.5	90.8	93.3
0.50	12.70	88.3	88.4	83.7	91.3	92.6	96.5
1.00	25.40	93.8	93.6	92.2	95.5	96.2	99.1
2.50	63.50	99.6	99.7	97.4	99.4	99.2	100.0
5.00	127.00	99.6	100.0	99.8	99.7	99.5	100.0

TABLE 8. PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY, EDWARDS AFB, CALIF.

Amount		Jan	Feb	March	Apr	May	June
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	81.7	81.8	82.6	86.7	95.1	98.8
Trace	Trace	88.0	88.9	89.6	93.8	98.6	99.5
0.01	0.25	88.9	89.5	91.3	94.8	99.0	99.5
0.05	1.27	91.7	92.1	93.8	96.4	99.1	99.5
0.10	2.54	93.5	93.5	95.5	97.6	99.4	99.5
0.25	6.35	96.9	95.6	98.0	99.0	100.0	99.9
0.50	12.70	98.8	98.3	99.1	99.6	100.0	100.0
1.00	25.40	99.8	99.6	99.8	100.0	100.0	100.0
2.50	63.50	100.0	100.0	99.9	100.0	100.0	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0
Amount		July	Aug	Sept	Oct	Nov	Dec
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	94.7	95.2	94.6	93.0	89.8	85.2
Trace	Trace	99.0	98.1	97.8	95.8	94.2	90.8
0.01	0.25	99.3	98.1	98.2	96.1	94.4	91.4
0.05	1.27	99.7	98.9	98.9	97.2	96.4	93.7
0.10	2.54	99.7	99.3	98.9	98.2	97.0	94.9
0.25	6.35	100.0	99.6	99.2	99.2	98.4	96.7
0.50	12.70	100.0	99.9	99.8	99.6	99.3	99.0
1.00	25.40	100.0	100.0	99.9	99.7	100.0	99.9
2.50	63.50	100.0	100.0	100.0	100.0	100.0	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 9. PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY, VANDENBERG AFB, CALIF.

Amount		Jan	Feb	March	Apr	May	June
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	69.4	70.4	61.7	70.4	71.8	70.0
Trace	Trace	79.1	75.9	72.2	80.4	94.0	94.8
0.01	0.25	81.1	76.9	74.6	82.5	96.8	97.7
0.05	1.27	83.5	81.4	83.9	87.9	98.0	100.0
0.10	2.54	88.3	84.4	85.9	90.8	98.8	100.0
0.25	6.35	91.5	90.4	91.5	95.4	99.6	100.0
0.50	12.70	95.1	94.4	96.3	97.5	100.0	100.0
1.00	25.40	98.3	96.9	98.7	99.2	100.0	100.0
2.50	63.50	99.9	99.9	99.5	100.0	100.0	100.0
5.00	127.00	100.0	100.0	99.9	100.0	100.0	100.0
Amount		July	Aug	Sept	Oct	Nov	Dec
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	62.4	63.4	77.9	79.4	73.3	73.8
Trace	Trace	98.2	94.9	95.4	95.1	82.6	80.6
0.01	0.25	98.9	98.1	95.8	95.5	83.3	83.1
0.05	1.27	100.0	98.8	97.5	95.9	85.9	87.4
0.10	2.54	100.0	99.5	97.9	96.7	87.4	89.2
0.25	6.35	100.0	99.9	98.7	97.5	90.0	93.5
0.50	12.70	100.0	100.0	99.9	98.7	94.4	97.1
1.00	25.40	100.0	100.0	100.0	99.5	98.8	99.6
2.50	63.50	100.0	100.0	100.0	99.9	99.9	100.0
5.00	127.00	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 10. PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY, NEW ORLEANS, LA.

Amount		Jan	Feb	March	Apr	May	June
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	77.1	70.2	73.6	79.7	75.9	72.2
0.01	0.25	77.7	71.1	74.1	79.9	76.4	72.6
0.05	1.27	80.9	74.5	78.1	81.9	78.0	77.7
0.10	2.54	85.7	76.4	81.0	83.6	82.9	82.3
0.20	5.08	89.1	80.4	82.8	87.0	86.5	85.3
0.50	12.70	94.0	88.8	88.6	91.2	92.2	90.3
1.00	25.40	97.4	93.8	92.9	95.3	95.6	93.8
2.00	50.8	98.9	97.8	97.9	97.8	99.0	98.8
5.00	127.00	99.7	99.7	99.7	100.0	100.0	100.0
10.00	254.00	100.0	100.0	100.0	100.0	100.0	100.0
Amount		July	Aug	Sept	Oct	Nov	Dec
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	54.5	70.1	69.2	84.4	83.4	77.6
0.01	0.25	55.8	71.3	71.1	85.6	84.7	78.2
0.05	1.27	61.4	74.4	76.3	88.2	85.7	80.7
0.10	2.54	67.4	79.3	79.2	90.5	87.4	83.2
0.20	5.08	73.3	83.5	84.4	93.4	89.4	85.2
0.50	12.70	81.5	92.4	90.3	96.0	94.0	91.9
1.00	25.40	91.5	95.7	94.5	98.0	97.3	95.2
2.00	50.80	96.7	98.2	98.0	99.7	98.3	99.4
5.00	127.00	100.0	100.0	99.0	100.0	99.7	99.7
10.00	254.00	100.0	100.0	100.0	100.0	100.0	100.0

TABLE 11. PROBABILITY THAT PRECIPITATION WILL NOT EXCEED A SPECIFIC AMOUNT IN ANY ONE DAY, WALLOPS TEST RANGE, VA. (BASED ON LANGLEY AFB DATA)

Amount		Jan	Feb	March	Apr	May	June
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	54.2	51.4	50.0	51.7	54.2	54.0
Trace	Trace	68.8	66.8	65.5	70.1	69.3	70.0
0.01	0.25	71.2	69.0	68.7	72.4	71.4	71.2
0.05	1.27	75.9	74.3	74.2	78.8	76.1	76.0
0.10	2.54	80.5	78.0	78.9	82.4	79.4	79.5
0.25	6.35	87.7	84.3	86.3	89.2	86.6	87.2
0.50	12.70	93.3	90.2	92.5	94.5	92.8	92.9
1.00	25.40	98.0	97.7	97.7	97.7	97.5	97.4
2.50	63.50	99.0	100.0	99.8	100.0	99.5	99.5
5.00	127.00	100.0	100.0	100.0	100.0	100.0	99.8
10.00	254.00	100.0	100.0	100.0	100.0	100.0	99.9
Amount		July	Aug	Sept	Oct	Nov	Dec
(in.)	(mm)	%	%	%	%	%	%
0.00	0.00	52.6	55.2	62.8	64.0	58.1	59.4
Trace	Trace	68.0	69.0	75.4	76.5	71.0	72.6
0.01	0.25	70.1	72.5	77.8	78.0	73.2	74.5
0.05	1.27	74.2	77.7	81.5	81.8	78.7	79.1
0.10	2.54	78.2	79.8	84.7	85.6	82.8	83.2
0.25	6.35	84.0	85.3	88.0	90.2	88.3	88.2
0.50	12.70	90.6	90.5	91.6	93.4	93.2	93.1
1.00	25.40	94.9	94.8	96.3	96.9	97.6	98.6
2.50	63.50	99.2	98.8	99.2	99.6	99.8	99.9
5.00	127.00	100.0	99.9	99.8	99.8	100.0	100.0

TABLE 12. HIGHEST RAINFALL RATE VERSUS DURATION FOR VARIOUS PROBABILITIES, GIVEN A DAY WITH RAIN FOR THE HIGHEST RAIN MONTH KENNEDY SPACE CENTER, FLA.

Duration	PERCENTILE											
	50				95				99			
	(in.)	(mm)	in. hr^{-1}	mm hr^{-1}	(in.)	(mm)	in. hr^{-1}	mm hr^{-1}	(in.)	(mm)	in. hr^{-1}	mm hr^{-1}
5 min	0.22	5.6	2.6	66.0	0.72	18.0	8.7	221.0	1.00	25.0	12.0	305.0
15 min	0.23	5.8	0.93	24.0	0.88	22.0	3.5	89.0	1.30	33.0	5.2	132.0
1 hr	0.25	6.4	0.25	6.4	1.17	30.0	1.17	30.0	1.93	49.0	1.93	49.0
6 hr	0.28	7.1	0.05	1.3	1.55	39.0	0.26	6.6	3.18	81.0	0.53	13.0
24 hr	0.43	10.9	0.02	0.5	2.62	67.0	0.11	2.8	5.00	127.0	0.21	5.3

TABLE 13. DISTRIBUTION OF RAINFALL RATES WITH HEIGHT FOR ALL LOCATIONS

Height (Geometric) Above Surface (km)	% Surface Rate
SRF	100
1	90
2	75
3	57
4	34
5	15
6	7
7	2
8	1
9	0.1
10 and over	< 0.1

2.5 Types of Ice Formation

The type of ice which will form on the outside exposed surfaces of cryogenic tanks is related to the temperature of the tank surface, precipitation rate, drop size, and the wind velocity (or tank velocity). In general, the larger the drop size and the higher the temperature, precipitation rate, and wind speed, the denser the ice will form until a condition is reached where surface temperatures are too high for ice to form. If the precipitation is at too high a temperature at relatively high precipitation rates and wind speed, it may warm the tank sufficient to melt ice which previously formed.

Table 14 summarizes ice types for various tank wall temperatures with moderate precipitation (over 10 mm hr^{-1}).

2.6 Hydrometeor Characteristics with Altitude

Raindrops falling on the surface may originate at higher altitude as some other form of hydrometeor, such as ice or snow. The liquid water content of these hydrometeors per unit volume would have a distribution similar to that given in Table 9 for rainfall.

A summary of the hydrometeor characteristics from Reference 6 is given in Table 15.

TABLE 14. ICE TYPES AS A FUNCTION OF TANK WALL TEMPERATURES

Temperature of Tank Wall		Type of Ice	Density Range		Remarks
°F	°C		lb ft^{-3}	g cm^{-3}	
23 to 32	-5 to 0	Clear ice	60	0.69	hard dense ice
0 to 23	-18 to -5	milky ice or clear ice with air bubbles	43-53	0.69-0.85	
below 15	below -9	Rime ice	18-25	0.29-0.40	crumbly

3.0 Snow

The accumulation of snow on a surface produces stress. For a flat horizontal surface, the stress is proportional to the weight of the snow directly above the surface. For long narrow objects, such as pipes or wires lying horizontally above a flat surface (which can accumulate the snow), the stress can be figured as approximately equal to the weight of the wedge of snow with the sharp edge along the object and extending above the object in both directions at about 45 deg to the vertical. (In such cases, the snow load would be computed for the weight of the snow wedge above the object and not the total snow depth on the ground). The weight of new fallen snow on a surface varies between 0.5 kg m^{-2} per cm of depth (0.25 lb $ft^{-2}in.^{-1}$) and 2.0 kg m^{-2} per cm of depth (1.04 lb $ft^{-2}in.^{-1}$), depending on the atmospheric conditions at the time of snowfall.

3.1 Snow Loads at Surface

Maximum snow loads for the following areas are:

a. Huntsville, Wallops Test Range, and Edwards Air Force Base. For horizontal surfaces a snow load of 25 kg m^{-2} (5.1 lb ft^{-2}) per 24-hr period (equivalent to a 10-in. snowfall) to a maximum of 50 kg m^{-2} (10.2 lb ft^{-2}) in a 72-hr period, provided none of the snow is removed from the surface during that time, should be considered for design purposes.

TABLE 15. SUMMARY OF HYDROMETEOR CHARACTERISTICS

Type of Hydrometeor	Altitude (km)	Drop Diameter (μm)		Concentration per Unit Volume (cm^3)		Liquid Water Content Per Unit Volume ($g\ m^{-3}$)		Ambient Temperature (°C)
	Range	Range	Rep.	Range	Rep.	Range	Rep.	Range ≈
Layer Clouds	sfc-1.5	<1-40	11	<10-10 000	500	<0.1-1	0.2	+30 to -15
Layer Clouds	2.5-7.5	<1-50	12	<20-1000	100	<0.1-1	0.2	+20 to -25
Layer Clouds (ice crystals)	7.5-15.0	<10-10 000	100	<0.1-10	0.2	<0.01-0.1	0.02	-10 to -55
Convective Clouds Fair Weather Cumulus	0.5-8.0	<1-75	12	<10-10 000	300	<0.1-1	0.5	+20 to -30
Cumulus Congestus	0.5-13.0	<1-200	25	<10-10 000	150	<1-10	4.0	+20 to -55
Continuous Type Rain	sfc-6.0	<500-3000	1000	<50-3000*	500*	<0.05-0.7	0.1	+30 to -15
Shower Type Rain	sfc-13.0	<500-7000	2000	<10-3000*	500*	<0.1-30	1.0	+30 to -55
Coalescence (Warm) Rain	sfc-5.0	<100-1000	500	<500-50 000*	3000*	<0.05-0.1	0.1	+30 to 0
Hail	sfc-13.0	<0.01-13cm	0.8cm	<0.5-1000*	50*	<0.1-0.9**	0.8**	+15 to -55
Ice and Snow Crystals	sfc-13.0	<100-20 000	5000	<1-1000*	100*	<0.001-0.7***	0.07***	+5 to -55

1. Rep.: Representative value or value most frequently encountered
* Per m^3
** Density of particles ($g\ cm^{-3}$)
*** Mass of crystals (mg)

d. Vandenberg Air Force Base, White Sands Missile Range, and Sacramento areas. For horizontal surfaces, a maximum snow load of 10 kg m^{-2} (2.0 lb ft^{-2}) per one 24-hr period should be considered for design purposes.

c. Kennedy Space Center and New Orleans area snow loads need not be considered.

3.2 Snow Particle Size

Snow particles may penetrate openings (often openings of minute size) in equipment and cause malfunction of mechanical or electrical components, either before or after melting. Particle size, associated wind speed, and air temperature to be considered are as follows:

a. Huntsville, Wallops Test Range, and Edwards Air Force Base. Snow particles 0.1-mm (0.0039-in.) to 5-mm (0.20-in.) diam.; wind speed 10 m sec^{-1} (19 knots); air temperature -17.8°C (0° F).

b. Vandenberg Air Force Base, White Sands Missile Range, and Sacramento areas. Snow particles 0.5-mm (0.020-in.) to 5-mm (0.20-in.) diam.; wind speed 10 m sec^{-1} (19 knots); air temperature -5.0° C (23° F).

4.0 Hail

Hail is one of the most destructive weather forces in nature, being exceeded only by hurricanes and tornadoes. Hail normally forms in extremely well-developed thunderstorms during warm weather and rarely occurs in winter months or when the air temperature is below 0° C (32° F). Although the average diameter of hailstones is 8 mm (0.31 in.) [5], hailstones larger than 12.7 mm (0.5 in.) in diameter frequently fall, while stones 50 mm (2.0 in.) in diameter can be expected annually somewhere in the United States. The largest measured hailstone in the Unites States was 137 mm (5.4 in.) in diameter and had a weight of 0.68 kg (1.5 lb) [7 and 8]. Three environmental effects on equipment must be considered.

The accumulation of hail, as with snow, stresses the object by its weight. Although hail has a higher density than snow, 2.4 kg m^{-2} cm^{-1} (1.25 lb $ft^{-2}in.^{-1}$), the extreme load from hail will not exceed the extreme snow load at any area of interest; therefore, the snow load design will adequately cover any hail loads expected.

Large hailstones, because of weight and velocity of fall, are responsible for structural damage to property [8]. To actually designate locations where hailstones, with specific sizes of hail, will fall is not possible. However, the following information can be used as a guide for design and scheduling (these values are most applicable to the design of ground support equipment and protective covering for the space vehicles during the transporting of vehicles).

4.1 Hail at Surface

a. Huntsville, Edwards Air Force Base, Gulf Transportation, New Orleans, Wallops Test Range, and White Sands Missile Range.

1. A maximum hailstone size of 50 mm (2 in.) in diameter with an occurrence probability of one time in 15 yr.

2. Damaging hailstorms occur most frequently between 3 p.m. and 9 p.m. during May through September. April is the month of highest frequency-of-occurrence of hailstorms for Huntsville and Gulf Transportation. March is the month of highest frequency-of-occurrence of hailstorms for White Sands Missile Range and Edwards Air Force Base; and May is the month of highest frequency-of-occurrence of hailstorms for Wallops Test Range.

3. The period of large hail (over 25 mm in diameter) will not be expected to last more than 15 min and should have a maximum total accumulation of 50 mm (2 in.) for depth of hailstones on horizontal surfaces.

4. Velocity of fall equals 30.5 m sec^{-1} (100 ft sec^{-1}) for each stone.

5. Wind speed equals 10 m sec^{-1} (33 ft sec^{-1}).

6. Density of hailstones equals 0.80 g cm^{-3} (50 lb ft^{-3}).

b. Eastern Test Range

1. A maximum hailstone size of 25.4 mm (1 in.) in diameter with an occurrence probability of one time in 30 yr may be expected.

2. Damaging hailstones occur most frequently between 3 p.m. and 9 p.m. during April through June. May is the month of highest frequency-of occurrence for hailstorms.

3. The period of large hail will not be expected to last more than 15 min and should have a maximum total accumulation of 12.5 mm (0.5 in.) for depth of hailstones on horizontal surfaces.

4. Velocity of fall equals 20 m sec^{-1} (66 ft sec^{-1}) for each stone.

5. Wind speed equals 10 m sec^{-1} (33 ft sec^{-1}).

6. Density of hailstones equals 0.80 g cm^{-3} (50 lb ft^{-3}).

c. Vandenberg Air Force Base will not need consideration for hail.

4.2 Distribution of Hail with Altitude.

Although it is not the current practice to design space vehicles for flight in thunderstorms, data on distribution with altitude are presented as an item of importance. The probability of hail increases with altitude from the surface to 5 km and then decreases rapidly with increasing height. Data on Florida thunderstorms, giving the number of times hail was encountered at various altitudes during aircraft flights [9], are given in Table 16 for areas specified in Paragraph 4.1.

TABLE 16. DISTRIBUTION OF HAIL WITH HEIGHT FOR ALL LOCATIONS [9]

Height (Geometric) Above Surface (km)	Occurrence of Hail % of Flights Through Thunderstorms
2	0
3	3.5
5	10
6	4
8	3

5.0 Laboratory Test Simulation

In the laboratory, simulated rain droplets are usually produced by use of a single orifice, mounted above the equipment being tested. Such a test will not necessarily duplicate the natural occurrence of precipitation and may or may not reflect the true effect of natural precipitation on the equipment since. a single orifice produces drops all nearly the same size.

Each test should be evaluated to determine if the following three factors which occur in natural precipitation are important in the test.

5.1 Rate of Fall of Raindroplets

Natural raindroplets will have usually fallen a sufficient distance to reach their terminal velocity (maximum rates of fall). Simulation of such rates of fall in the laboratory requires the droplets to fall a suitable distance. Large droplets (4-mm diam. and greater) will require about 12 m (39 ft) to reach terminal velocity.

The higher velocities of fall will modify the effect of the droplets on equipment. Values of terminal velocities of water droplets were measured by Gunn and Kinzer [10]. Their results gave the values in Table 17. Reference 10 should be obtained for more detailed information.

TABLE 17. VALUES OF TERMINAL VELOCITIES OF WATER DROPLETS [10]

Drop Diameter (m)	Terminal Velocity ($m\ sec^{-1}$)
1	4.0
2	6.5
3	8.1
4	8.8
5	9.1
5.8	9.2

Gunn and Kinzer [10] found that water droplets greater than 5.8 mm would usually break up before the terminal velocity was reached.

5.2 Raindrop Size and Distribution

Normal rainfall has a variety of drop sizes with a distribution as shown in Figure 3. Figure 3 illustrates the wider distribution of droplet sizes in the heavier rain which has the larger droplets. The maximum drop diameter distribution could be adequately simulated by a number of orifices, all at the same water pressure, to produce droplets of about 1-, 2-, 3-, and 4- and 5-mm diam. For the median drop diameter, the use of a single orifice to produce 1-mm droplets would be suitable.

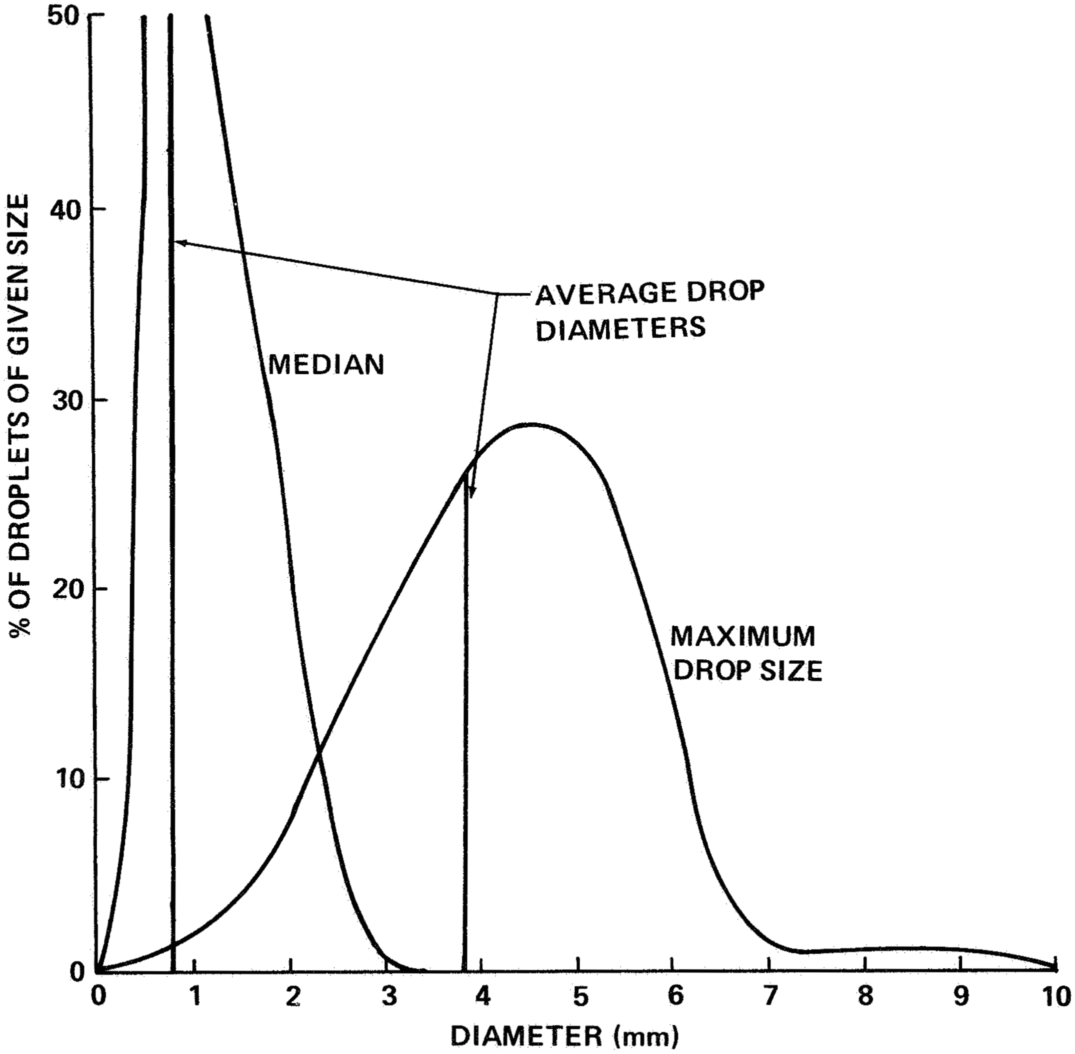

Figure 3. Distribution of drop sizes of rain.

5.3 Wind Speed

In most cases of natural rain there will be wind blowing near horizontal. This wind will modify the droplet paths from a vertical path to a path at some angle to the vertical; thus causing the rain droplets to strike at an angle. In addition, unless the equipment is streamlined in the direction of the wind, small vortices may develop at the surface of the equipment. These vortices may cause a considerable amount of the precipitation to flow in a variety of directions, including upward against the bottom of the equipment.

Studies of thunderstorms with rainfall rates from 12.7 to 7 mm hr^{-1} (0.5 to 3.0 in. hr^{-1}) with relationship to wind speeds occurring at the same time have shown an average mean wind speed of 5 m sec^{-1} for all storms combined. Peak winds were as high as 16 m sec^{-1}. All storms, except one with rates exceeding 25 mm hr^{-1}, had peak winds at least 5 m sec^{-1} greater than the mean wind for the same storm.

5.4 Temperatures

The air temperature at the ground usually decreases several degrees at the start of rainfall with rates in excess of 12.7 mm hr^{-1} (0.5 in. hr^{-1}). The amount of the temperature decrease is greatest in the summer when the temperature is high [greater than 32°C (90°F)] with the final temperature approximately 24°C (75°F). In the winter the temperature decrease is usually about 28°C (5°F). At the end of the rainfall the summer temperature will increase again to nearly the same values as before the storm, but in the winter there is no general pattern of warming. This decrease in temperature is caused by the water droplets being colder than the surface air temperature.

5.5 Recommended Items to Include in Laboratory Rainfall Tests

The following items need to be considered in rainfall tests in the laboratory:

a. Raindrop size distribution.
Rates less than 25 mm hr^{-1} — drop size of 1 mm.
Rates greater than 25 mm hr^{-1} — drop size from 1 to 5 mm.

b. Rate of fall of drops. Drops should fall at least 12 m to obtain terminal velocity.

c. Wind Speed. A mean wind of 5 m sec^{-1} with gusts of 15 m sec^{-1} of 30-sec duration at least once in each 15-min period.

d. Temperature. The temperature in the chamber should decrease from 32° C (90° F) to 24° C (75° F) at the start of rainfall for representative summer tests and should be maintained at 10° C (50° F) for winter tests. The decrease in air temperature may be obtained by using water at, or slightly below 24° C for the summer tests.

5.5.1 Idealized Rain Cycle, Kennedy Space Center, Fla.

For design studies and laboratory tests, the idealized rain cycle shown in Figure 4 and Table 18 should be used. The rainfall in the cycle is representative of the 95th percentile Cape Kennedy rainfall on any day with rain during the worst rain month and the associated wind speeds, temperatures, and drop sizes expected with the rain.

6.0 Rain Erosion

6.1 Introduction

With the advent of high-speed aircraft a new phenomenon was encountered in the erosion of paint coatings, structural plastic components, and even metallic parts by the impingement of raindrops on surfaces. This was first observed soon after World War II on fighter aircraft capable of speeds over 178 m sec^{-1} (400 mph) [11]. This initiated rain erosion research at the Air Force Materials Laboratory, Wright-Patterson Air Force Base and at the Royal Aircraft Establishment, Farmborough, England. Tests conducted by the British Ministry of Aviation at the Royal Aircraft Establishment [12] have resulted in a table of rates of erosion for various materials and coatings. These materials and coatings were tested at speeds of 220 m sec^{-1} (428 knots). At the Air Force Materials Laboratory, a number of rotating (whirling) arm apparatuses have been used. The current rotating arm apparatus will permit testing of samples of materials at speeds up to 403 m sec^{-1} (900 mph) (Mach 1.2) with simulated rainfall variable through a wide variety of rates. Normally the tests are made at 224 m sec^{-1} (500 mph) and at 25.4 mm hr^{-1} (1 in. hr^{-1}) or 50.8 mm hr^{-1} (2 in. hr^{-1}) of rainfall [13]. A number of flight tests using F-80 aircraft in rain were made and compared with the rotating arm tests. The ranking of the test materials for rain erosion was similar for the variety of materials tested, but the time to erode materials varied because of differences

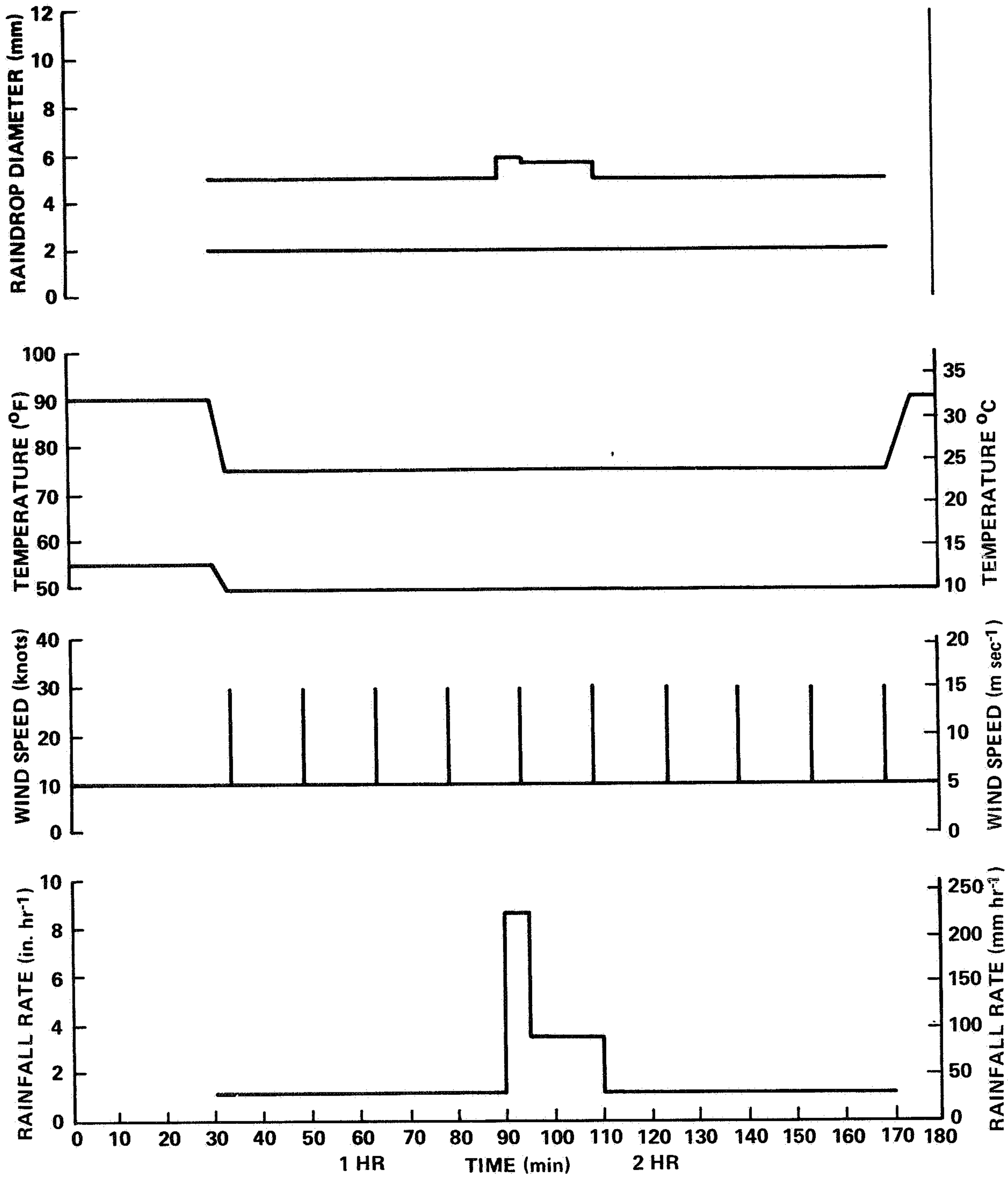

Figure 4. Idealized Rain Cycle, Kennedy Space Center, Fla.; based on highest rain month.

TABLE 18. IDEALIZED RAIN CYCLE, KENNEDY SPACE CENTER, FLA.; BASED ON HIGHEST RAIN MONTH

Cycle	Rainfall Rate		Wind Speed		Raindrop Size		Temperature			
							Summer		Winter	
min	mm hr^{-1}	in. hr^{-1}	m sec^{-1}	knots	largest mm	average mm	°F	°C	°F	°C
0	0	0	5.1	10	0	0	90	32	55	13
30	3.0	1.17	5.1	10	5.0	2	90	32	55	13
32	3.0	1.17	5.1	10	5.0	2	75	24	50	10
33.5	3.0	1.17	15.4	30	5.0	2	75	24	50	10
34	3.0	1.17	5.1	10	5.0	2	75	24	50	10
48.5	3.0	1.17	15.4	30	5.0	2	75	24	50	10
49	3.0	1.17	5.1	10	5.0	2	75	24	50	10
63.5	3.0	1.17	15.4	30	5.0	2	75	24	50	10
64	3.0	1.17	5.1	10	5.0	2	75	24	50	10
78.5	3.0	1.17	15.4	30	5.0	2	75	24	50	10
79	3.0	1.17	5.1	10	5.0	2	75	24	50	10
90	22.0	8.7	5.1	10	5.9	2	75	24	50	10
93.5	22.0	8.7	15.4	30	5.9	2	75	24	50	10
94	22.0	8.7	5.1	10	5.9	2	75	24	50	10
95	8.9	3.5	5.1	10	5.8	2	75	24	50	10
108.5	8.9	3.5	15.4	30	5.8	2	75	24	50	10
109	8.9	3.5	5.1	10	5.8	2	75	24	50	10
110	3.0	1.17	5.1	10	5.0	2	75	24	50	10
123.5	3.0	1.17	15.4	30	5.0	2	75	24	50	10
124	3.0	1.17	5.1	10	5.0	2	75	24	50	10
138.5	3.0	1.17	15.4	30	5.0	2	75	24	50	10
139	3.0	1.17	5.1	10	5.0	2	75	24	50	10
153.5	3.0	1.17	15.4	30	5.0	2	75	24	50	10
154	3.0	1.17	5.1	10	5.0	2	75	24	50	10
168.5	3.0	1.17	15.4	30	5.0	2	75	24	50	10
169	3.0	1.17	5.1	10	5.0	2	75	24	50	10
170	0	0	5.1	10	0	0	75	24	50	10
180	0	0	5.1	10	0	0	90	32	50	10

in the intensities of the various environments. The natural erosion conditions included hail, ice crystal, and liquid water impingement [14].

6.2 Rain Erosion Criteria

Rain erosion may be severe enough to affect the performance of a space vehicle. Sufficient data are not available to present specific extreme values of exposure for various materials used in design. Experience and results of the various tests indicate that materials should be carefully considered. Any materials in which failure in rain erosion would have an effect on the mission should be subjected to tests for rain erosion. Criteria for rain-eriosion tests should be based on Table 19.

TABLE 19. RAIN EROSION CRITERIA

Rainfall Rate ($mm\ hr^{-1}$)	Rainfall Rate ($in.\ hr^{-1}$)	Duration of Test (min)	Velocity** of Test	Raindrop Size (mm)	Angle of Attack (deg)
2.5	0.10	60	selected by the maximum velocity of the space vehicle in areas of rainfall	2	selected by use of material, i.e. 10° 20°, 40°, etc. (wind and tail leading edges) 70°, 80°, 90° nose cap
12.5	0.50	10		2	
25.4	1.00	10		2	
50.8	2.00*	10		2	

* A rate of 50.8 mm hr^{-1} (2.00 in. hr^{-1}) would only be used for the most critical materials.

** The velocities selected could modify the duration of test since any areas in clouds of rainfall rates in excess of 12.8 mm hr^{-1} (0.5 in. hr^{-1}) would be limited in size ~ 97 km (~ 60 mi) and the length of time for the space vehicle to travel a distance of 97 km would decrease with increased speed.

Tests by A. A. Fyall at the Royal Aircraft Establishment [15] on single rain droplets have shown that the rain erosion rate may increase considerably with lower air pressure (higher altitude) because of the lower cushioning effect of the air on the droplets at impact.

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APPROVAL

PRECIPITATION CRITERIA GUIDELINES FOR USE IN AEROSPACE VEHICLE DEVELOPMENT

By Glenn E. Daniels

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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